

Cryocooler resonance characterization *

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An important issue in the design and scaling-up of Stirling cryocoolers is achieving good drive motor efficiency and launch survivability. The important common thread linking these two topics is the dynamic resonant response of the compressor and displacer moving masses. The fundamental equations governing cryocooler mechanical efficiency and launch vibration response are presented and explored in terms of their implications for cooler design. The resonant frequency, damping and drive motor force parameters associated with the cooler are shown to be key to efficient operation. Means of measuring these parameters are presented and shown to have broad applicability to additional parameters such as drive stiction and vibration transmitted to the instrument. The resonant parameters of the BAe 55 K AIRS proof-of-concept cooler are used as an example to demonstrate the good correlation between the analytical fundamentals and the measured characteristics of a state-of-the-art cryocooler design.

Keywords: cryocoolers; resonance characterization; space cryogenics

The growing demand for long-wavelength infrared imaging instruments for space observational applications, together with the successful flight of the Oxford University ISAMS Stirling cycle cooler, has led to the ongoing development of several second generation Stirling cycle cryocoolers that are scaled up in size from the original Oxford design. To ensure the success of these cooler developments, the Jet Propulsion Laboratory (JPL) has been carrying out an extensive cryocooler characterization programme since 1989¹. Following extensive characterization of the British Aerospace (BAe) 80 K Oxford cooler²⁻⁶, more recently the JPL programme has been expanded under Air Force and NASA sponsorship to focus on the larger capacity BAe 55 K and 50–80 K coolers⁷, and similar coolers from other manufacturers⁸.

An important topic with the new larger cooler designs is the subject of cooler drive motor efficiency and launch survivability. The important common link between these two topics is the dynamic resonant response of the compressor and displacer moving masses. The resonant frequency, damping and drive motor force parameters associated with the cooler are key to efficient operation, and means of measuring these parameters have broad applicability to additional parameters such as drive stiction and vibration transmitted to the instrument.

This paper uses the BAe 55 K cooler as an example to explore the important cooler drive resonance parameters, including the fundamental governing equations and useful measurement techniques.

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Linear cooler drive fundamentals

Split Stirling coolers of the Oxford/BAe type are based on linear drive motors in both the compressor and displacer, as shown in *Figure 1*. In the Oxford cooler concept, the compressor piston and expander displacer are both suspended on flexure springs that allow precise linear motion in the axial drive direction, but minimize excursion in the radial piston-clearance direction. This provides long life by minimizing piston or displacer contact and wear during operation. In most linear drive coolers, the drive force is provided by a voice-coil driven permanent magnet motor, similar to that used in a conventional audio speaker.

Linear drive motor relationships

In a linear voice coil drive motor, the applied force is proportional to the electrical current in the drive coil, the flux density of the magnetic field in the gap occupied by the coil and the total length of coil wire that is in the magnetic field, i.e.⁹

$$F/i = BL \quad (1)$$

where: F = motor force (N); i = coil current (A); B = magnetic flux density in the gap (T); and L = length of coil wire in the gap (m).

In designing an efficient linear drive motor, consideration must be given to minimizing the i^2R losses in the coil and achieving a coil that is well matched to the cooler drive voltage. The back e.m.f. generated by the

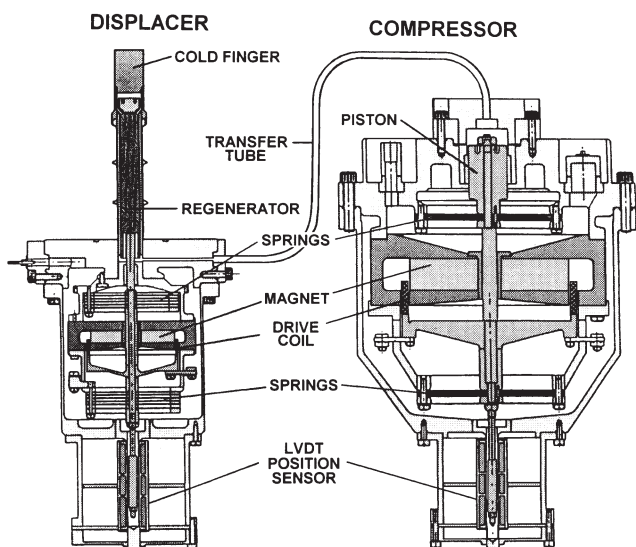


Figure 1 Cross-section of Oxford-style Stirling cycle cooler displaying linear drive motors and flexure spring suspension systems

coil when it is moving in the magnet gap is the primary voltage-establishing parameter. Interestingly, the back e.m.f. for a given coil velocity is determined by the same physical parameters as govern the generated drive force, i.e.⁹

$$E/\dot{x} = BL \quad (2)$$

where E = generated back-e.m.f. coil voltage (o-p) (V) and \dot{x} = coil velocity (o-p) (m s^{-1}).

This back-e.m.f. motor constant can be easily measured by driving the cooler motor externally (e.g. pneumatically) and measuring the generated voltage for a given stroke; thus

$$E/\dot{x} = 450E_{\text{rms}}/(fx_{\text{p-p}}) \quad (3)$$

where: E_{rms} = open-circuit back-e.m.f. voltage (V, rms); f = drive frequency (Hz); $x_{\text{p-p}}$ = stroke amplitude (p-p) (mm); and $450 = \sqrt{2} \times 10^3/\pi$.

When the cooler is in operation, the required cooler drive voltage is the sum of the back-e.m.f. voltage and the iR drop in the drive coil due to the drive current (i) and the coil impedance ($Z \approx R$); i.e.

$$V = iR + E \quad (4)$$

Note that the terms in Equation (4) are vectors, and scalar addition can only be used if both iR and E are in-phase. This in-phase condition turns out to be the maximum efficiency condition, and thus is a primary goal of the compressor drive suspension design.

Drive motor efficiency

Linear motors consume power in three principal ways: 1, by doing useful work on the applied load; 2, by dissipating i^2R losses in the drive coil; and 3, by doing work to overcome various internal frictional forces impeding the motor motion. These frictional forces, caused by windage, mechanical friction and eddy current forces, may become significant in a poor motor design. Because i^2R losses are generally the dominant

loss term in a good motor, cooler motor efficiency has historically been expressed as¹⁰

$$\text{Motor efficiency} = (\text{input power} - i^2R)/(\text{input power}) \quad (5)$$

Because power is the integrated dot product of force and velocity, only the component of an applied force that is in-phase with the piston velocity consumes input power. Similarly, from Equations (1) and (2), only the current component in-phase with the back-e.m.f. does useful work. Currents 90° out of phase with the velocity can be thought of as capacitive or inductive circulating currents that only contribute to i^2R losses. A motor that operates efficiently thus has a near unity power factor, where power factor is defined as the cosine of the phase angle between the input drive voltage and the input drive current. The power factor is also the input power consumed divided by the product of the true rms voltage times the true rms current.

A key goal of cooler design is thus to minimize or eliminate drive currents or forces that are 90° out of phase with the drive velocity. Because the mechanical and gas spring forces restraining the piston movement and the inertial forces required to accelerate the piston are opposite in sign and 90° out of phase with velocity, minimizing the sum of these forces is key to high cooler efficiency. Since the inertial forces are dependent on the drive frequency and moving mass, and the stiffness forces are not, the sum of these 90° forces can be manipulated and nulled by appropriately selecting the drive frequency and the moving mass. This condition of equal and opposite spring and inertial forces is known as the resonant condition for a spring-mass system, and occurs at a single drive frequency known as the natural frequency. Achieving resonance at the cooler drive frequency is thus important to high cooler motor efficiency.

Cooler drive resonance parameters

The primary determiners of the compressor resonant frequency are the moving mass of the compressor and the total elastic spring constant of the combined compressed gas and suspension springs. Since the gas and suspension springs act in parallel, the total elastic spring constant (K) is given by

$$K = K_s + K_g \quad (6)$$

where K_s = spring constant of suspension springs (N m^{-1}) and K_g = spring constant of the compressed gas (N m^{-1}).

Generally the gas spring of the compressor is modestly stiff compared to the suspension springs, and thus the gas spring contributes the majority of the total stiffness. Because the spring constant of the gas is roughly proportional to the fill pressure, inversely proportional to the working gas volume and proportional to the fourth power of the piston diameter, the spring constant of the compressor is very sensitive to its size and geometry. In contrast, the gas spring of the displacer is generally relatively weak compared to the stiffness of the suspension springs, and thus the stiffness of the displacer is principally determined by the

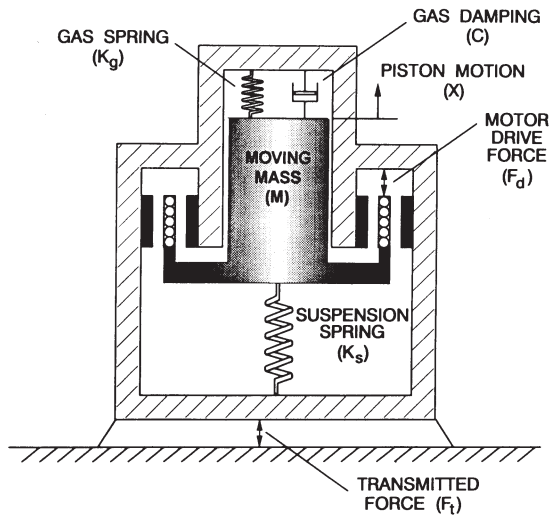


Figure 2 Schematic representation of cryocooler compressor and displacer as single-degree-of-freedom spring-mass-damped systems

suspension spring stiffness. The displacer stiffness is therefore much less sensitive to scaling of the cooler's size.

These mechanical elements of a linear drive, Stirling cycle cooler combine to closely approximate a classic single-degree-of-freedom spring-mass system, as schematically illustrated in *Figure 2*. This system has a natural frequency defined by

$$f_o = 1/2\pi [K/M]^{1/2} \quad (7)$$

where: f_o = natural frequency (Hz); K = spring constant (N m^{-1}); and M = moving mass (kg).

Because of the work performed on the gas internal to the cooler, the resonant piston and displacer systems also include relatively large velocity dependent forces, denoted by the damper (C) in *Figure 2*. The degree of damping is described by the ratio (ζ) of the damping coefficient (C) to the critical damping coefficient (C_c). The critical damping coefficient is defined as

$$C_c = 2(KM)^{1/2} = 4\pi M f_o \quad (8)$$

where C_c = the critical damping coefficient (N s m^{-1}). Because the damper force ($F_c = C \times \text{velocity}$) is in-phase with the velocity, it is the only power dissipating force in a dynamic system. The level of power dissipation is given by

$$P_c = 1/2 C \dot{x}^2 = 4.935 \times 10^{-6} f^2 x_{p-p}^2 \zeta C_c \quad (9)$$

where: P_c = power dissipation (W); \dot{x} = piston/displacer velocity (o-p) (m s^{-1}); f = drive frequency (Hz); x_{p-p} = peak-to-peak displacement amplitude (mm); C = damping coefficient (N s m^{-1}); ζ = damping ratio (C/C_c); C_c = critical damping coefficient (N s m^{-1}); and $4.935 = \pi^2/2$.

Response to sinusoidal forced excitation

The classic solution for the amplitude response of the moving mass to a sinusoidal drive force ($F_d \sin 2\pi ft$) is given by¹¹

$$x/x_o = 1/\{[1 - (f/f_o)^2]^2 + [2\zeta(f/f_o)]^2\}^{1/2} \quad (10)$$

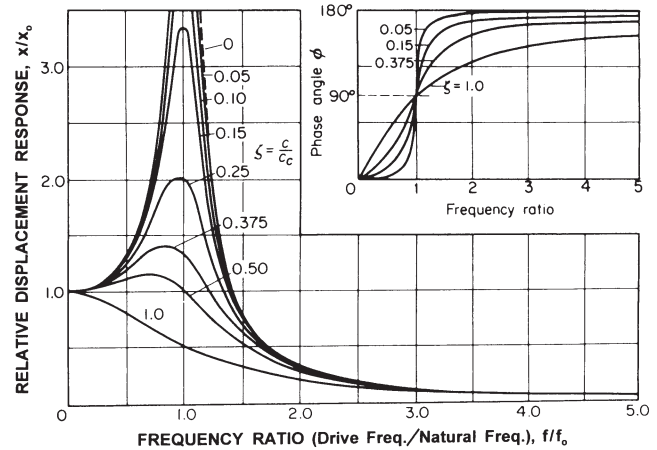


Figure 3 Frequency response curves for single-degree-of-freedom (1 d.o.f.) system excited by a sinusoidal force

where x = piston/displacer motion amplitude (o-p) and x_o = zero frequency amplitude = F_d/K . Equation (10) is plotted in *Figure 3* in terms of the damping ratio ($\zeta = C/C_c$) and the frequency ratio (f/f_o). When a modest degree of damping is present, the maximum response amplitude and amplitude gain are seen to occur at a frequency that is somewhat less than the natural frequency. This frequency of maximum response is referred to as the resonant frequency (f_R). The amplitude gain (Q_o) at the natural frequency is directly related to the damping ratio (ζ) by

$$Q_o = C_c/2C = (2\zeta)^{-1} \quad (11)$$

Another situation of interest to the cryocooler integrator is the vibration force transmitted to the host instrument from the cooler's moving mass. If the cooler mount is very rigid (i.e. the mount resonance is well above the cooler drive frequency) then the force transmission ratio is given by¹¹

$$F_t/F_d = (f/f_o)^2 / \{[1 - (f/f_o)^2]^2 + [2\zeta(f/f_o)]^2\}^{1/2} \quad (12)$$

where F_t = vibration force amplitude (o-p) transmitted to the cooler mount and F_d = force amplitude (o-p) from cooler motor drive coil. Equation (12) is plotted in *Figure 4*. Note from *Figures 3* and *4* that high frequency drive forces caused by non-linearities and

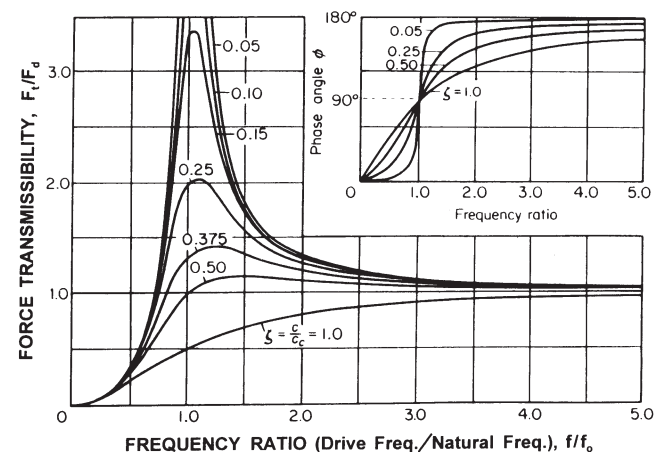


Figure 4 Force transmissibility curves for 1 d.o.f. system excited by a sinusoidal force

current harmonics above the drive frequency are directly transmitted to the support structure and cause little piston motion. This relationship will be used later to measure the drive motor force/current transfer function as defined in Equation (1). Note also that they are 90° out of phase with the piston velocity; thus they do no work, but contribute directly to i^2R losses.

Characterization of BAe cooler resonance parameters

Although the analytical understanding of the cooler drive parameters – as articulated in the above equations – is reasonably well developed, obtaining the actual parameter values generally requires measurements. This is because many of the cooler parameters such as the spring constant of the compressed gas, the flux density in the voice coil drive, and the velocity dependent work in the compressor and displacer are only roughly predictable.

To measure the compressor and displacer resonance parameters, the BAe 55 K cooler was mounted on JPL's force dynamometer; this allows the compressor and displacer transmitted interface forces (F_t), as well as the piston and displacer strokes, to be quantified. The actual test involves conducting a constant amplitude, sinusoidal-current frequency sweep through the region of the cooler's resonant frequency. Because of the relationship between current and drive force as described by Equation (1), the test closely approximates a constant amplitude sinusoidal force input over the range of drive frequencies. Compressor and displacer motion amplitude and phase relative to the drive current are measured using the cooler's built-in position sensing (LVDT) transducers.

Plots of the measured piston/displacer resonant response closely approximate the vibration frequency response and force transmissibility curves presented in Figures 3 and 4. The cooler's parameter values are quantified by least-squares fitting the response equations [Equations (10) and (12)] to the measured curves. Table 1 summarizes the measured resonance and drive parameters for the BAe 55 K AIRS cooler at both ambient and cryogenic temperatures. The ambient-temperature data are those applicable during launch and cooler start-up, while the cryogenic data are applicable for normal operation when the cold-tip is at cryogenic temperatures. Note that the measurement technique provides for complete characterization of the cooler, including such parameters as the motor force constant, the moving mass, the spring stiffness and the damping. Details of the measurements are described below.

Compressor drive resonance characteristics

As seen in Table 1, the resonance characteristics of the compressor change somewhat between ambient and cryogenic temperatures. This is because the stiffness of the gas spring drops with decreasing gas pressure as gas density increases in the cold-finger. Note that the damping also increases somewhat at cryogenic temperatures. This damping at cryogenic temperatures is a measure of the losses in the refrigerator when the displacer is not operating; these losses can be computed

Table 1 Summary of drive resonance parameters for BAe 55 K cooler

	Cold-tip temperature	
	Ambient	Cryogenic
Compressor:		
Natural frequency (Hz)	58.5	50.2
Resonant frequency (Hz)	56.0	47.0
Motor force constant (N A^{-1})	12.7	12.7
Moving mass (g)	213	213
Spring stiffness (N mm^{-1})	28.8	21.2
Critical damping coefficient, C_c (N s m^{-1})	157	134
Damping ratio, C/C_c	0.17–0.21	0.19–0.27
Displacer:		
Natural frequency (Hz)	37.0	39.0
Resonant frequency (Hz)	36.0	35.0
Motor force constant (N A^{-1})	7.4	7.4
Moving mass (g)	35.1	35.1
Spring stiffness (N mm^{-1})	1.89	2.10
Critical damping coefficient, C_c (N s m^{-1})	16.3	17.1
Damping ratio, C/C_c	0.15–0.17	0.25–0.31

using Equation (9). In contrast, the ambient damping is important in determining the extent of piston attenuation during launch, and will be revisited later when discussing launch behaviour.

Figures 5 and 6 display example frequency response

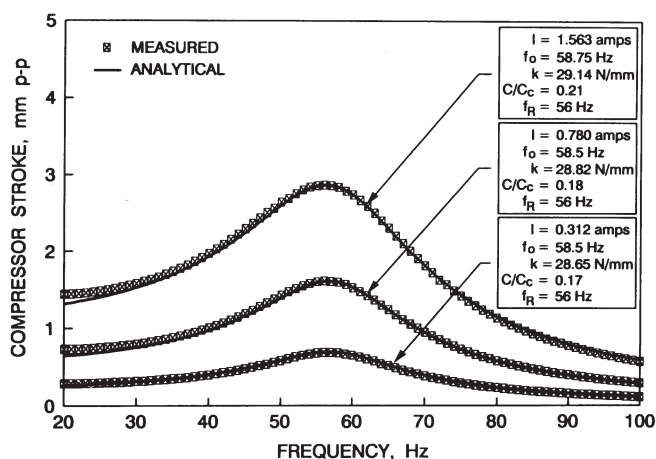


Figure 5 Measured frequency response of BAe 55 K compressor or piston for constant amplitude sinusoidal drive current

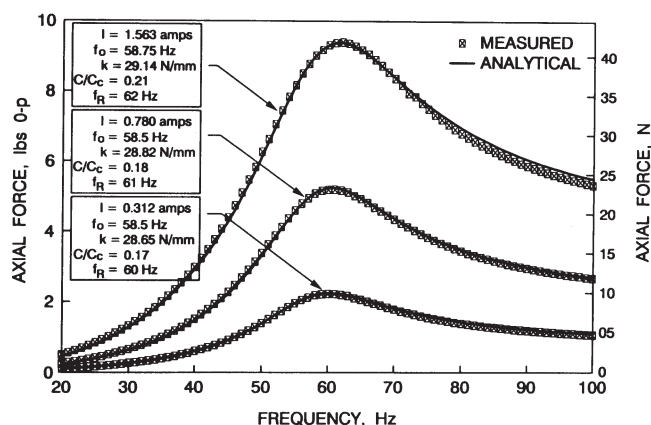


Figure 6 Measured force transmissibility response of BAe 55 K compressor for constant amplitude sinusoidal drive current

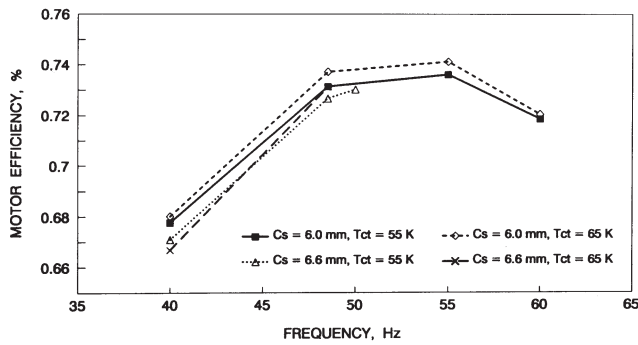


Figure 7 Motor efficiency of BAe 55 K compressor versus drive frequency

data for both the compressor stroke and transmitted force at three different drive-current levels. Note that the damping also increases somewhat with increasing stroke; this is typical of most structural systems. The natural frequency at cryogenic temperatures is found to be desirably close to the 48.5 Hz drive frequency and leads to measured power factors around 0.98. The measured drive motor efficiency of the compressor is presented in *Figure 7*, and can be seen to closely match the measured resonance response. The maximum efficiency of $\approx 74\%$ is typical for motors of this type.

Displacer drive resonance characteristics

As seen in *Table 1*, the primary feature of the displacer that changes between ambient and cryogenic temperatures is the damping. This is no doubt linked to the increased density of the gas in the cold-finger at cryogenic temperatures. Because the damping force is in-phase with the displacer velocity, this high degree of damping represents an important power loss term in the displacer. Using Equation (9) this power dissipation is computed to be ≈ 0.45 W for a nominal displacer stroke of 3 mm (p-p) and with the compressor stroke restrained to zero. *Figures 8* and *9* display example frequency response data for both the displacer stroke and transmitted force at three different drive-current levels.

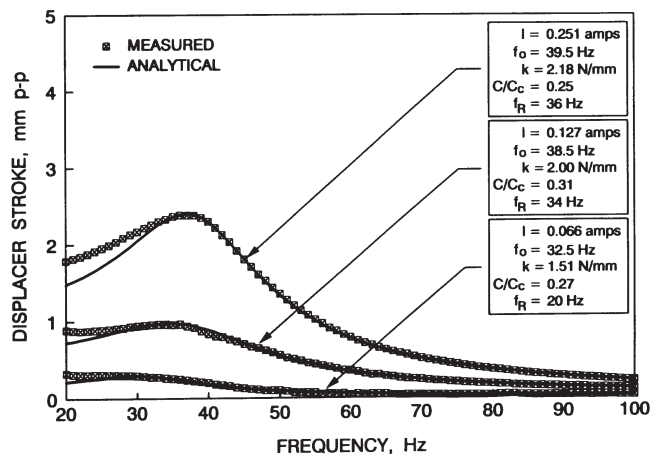


Figure 8 Measured frequency response of BAe 55 K displacer for constant amplitude sinusoidal drive current

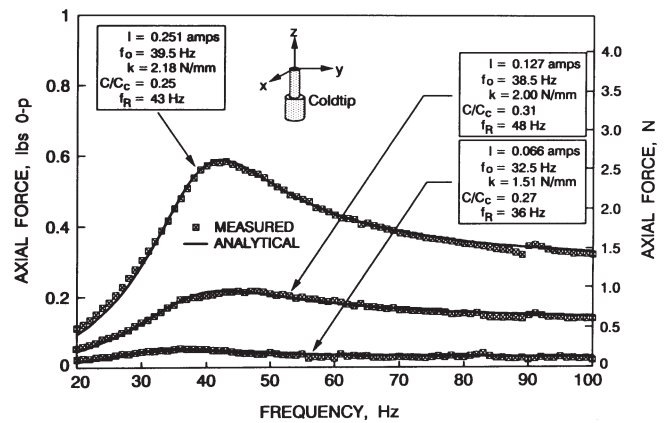


Figure 9 Measured force transmissibility response of BAe 55 K displacer for constant amplitude sinusoidal drive current

Resonance effects on launch vibration response

In addition to being important to cooler electrical efficiency, motor resonance characteristics are also key to the amplitude of piston and displacer motions excited during launch. The key issue is whether the excited motions during launch will cause the cooler piston and/or displacer assembly to hit their end stops and possibly damage the internal parts or knock the cooler out of alignment. The fundamental equation describing the amplitude of vibration for a given launch acceleration level (\ddot{x}) is the same as Equation (10), except that the input force is the negative product of the moving mass and the launch acceleration; i.e. $F_d = -M\ddot{x}$. Thus

$$x/x_0 = 1/\{[1 - (f/f_0)^2]^2 + [2\zeta(f/f_0)]^2\}^{1/2} \quad (13)$$

where: x = piston/displacer motion amplitude (o-p) (m); x_0 = zero frequency amplitude $= M\ddot{x}/K = \ddot{x}/(2\pi f_0)^2$; \ddot{x} = launch acceleration amplitude (o-p) (m s^{-2}) $= 9.81 \times [\text{launch acceleration in } g \text{ (o-p)}]$; f = launch acceleration frequency (Hz); and f_0 = piston/displacer natural frequency (Hz). Note that x_0 reduces to $\ddot{x}/(2\pi f_0)^2$, which is the displacement amplitude of the base excitation motion at the natural frequency of the cooler. Thus, the higher the natural frequency, the lower will be the resulting piston/displacer motion during launch for a given launch acceleration level. Because of the similarity between Equations (10) and (13), *Figure 3* is also a plot of Equation (13).

From *Figure 3* it is clear that another means of controlling piston/displacer motion is to increase the damping, and thereby reduce the gain (Q_0) at the compressor and the displacer natural frequencies. *Figure 10* summarizes the computed piston/displacer motion amplitude (p-p) for a 15g (o-p) sinusoidal launch acceleration input and for various piston/displacer natural frequency and gain (Q_0) levels. The 15g level is a typical launch acceleration requirement for small spacecraft devices with resonant frequencies below 100 Hz^{12,13}. Note that the limited travel of the displacer makes it the more difficult element to protect against over-stroking during launch.

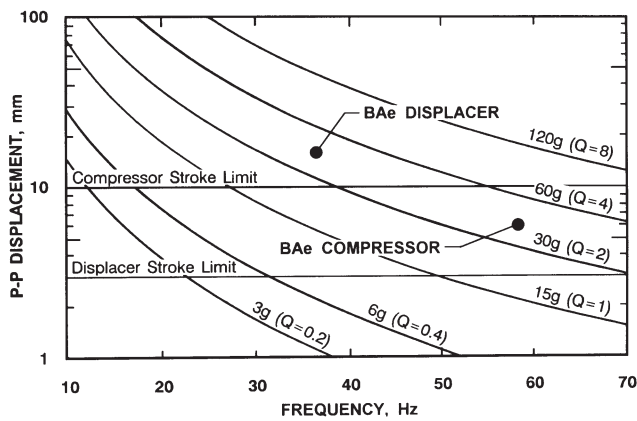


Figure 10 Motion amplitude (p-p) at piston/displacer natural frequency (f_o) for 15g (o-p) sinusoidal vibration input and various amplification factors (Q_o)

Effects of shorting the drive coils

One means of greatly increasing the damping during launch without imposing an efficiency penalty on the operating cooler is to electrically short the compressor and displacer drive coils. When the coils are shorted, the back e.m.f. voltage developed by each coil [Equation (2)] generates a current proportional to the coil velocity and limited by the coil circuit resistance. This current develops a damping force (F_c) opposing the coil motion as described by Equation (1). Thus

$$F_c = [(force/amp) \times (volts/velocity)/resistance] \times (coil velocity) \\ = C_e \dot{x} \quad (14)$$

where: F_c = electrical damping force (N); C_e = electrical damping coefficient ($N s m^{-1}$); and \dot{x} = coil velocity ($m s^{-1}$).

The components of the electrical damping coefficient are available from Equations (1), (2) and (3); thus

$$C_e = (BL)^2/R \\ = (N/A)^2/R \\ = (E/\dot{x})^2/R \quad (15)$$

where: B = magnetic flux density in the gap (T); L = length of coil wire in the gap (m); R = total coil resistance including external wiring (Ω); and E/\dot{x} = back-e.m.f./velocity from Equation (3). Note that BL is the motor force constant (in N/A), which is easily measured and is reported in Table 1 for the BAe 55 K cooler. Using this cooler as an example, the electrical damping coefficient obtained by shorting the 0.88Ω compressor coil is given by

$$C_e = (12.7 N/A)^2/0.88 \Omega = 183 N s m^{-1}$$

When combined with the existing damping ($\zeta = 0.17$) in the compressor, this gives a damping ratio of

$$\zeta_{total} = \zeta + C_e/C_c = 0.17 + 183/157 = 1.34 \quad (16)$$

where $C_c = 157 N s m^{-1}$ (from Table 1).

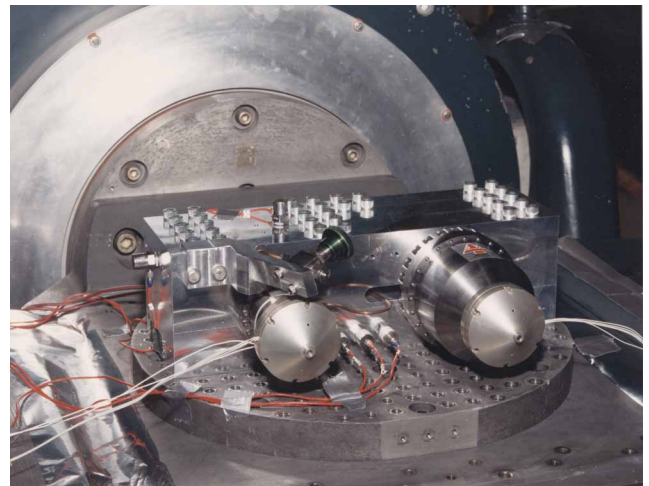


Figure 11 BAe 55 K cooler mounted in JPL launch vibration test facility

Launch vibration testing of BAe 55 K cooler

To measure the compressor and displacer response to launch excitation and validate the computations for the effect of motor shorting, the BAe 55 K cooler was rigidly mounted to a large launch vibration test shaker, as shown in Figure 11. The cooler was then subjected to low frequency sinusoidal acceleration frequency sweeps from 15 to 100 Hz at a constant amplitude of 3g (o-p) parallel to the cooler drive axis. During the 2 octave per minute sweeps, the cooler piston and displacer motions were recorded using the cooler's internal (LVDT) position transducers. The resulting piston/displacer amplitude versus frequency plots are presented in Figures 12 and 13 for a variety of coil-shortening resistances ranging from open-circuit to short-circuit. Note that the frequency response curves closely resemble those in Figures 5 and 8 for the electrically driven cooler. Similarly, Table 2 presents the good agreement between the response parameters measured in the 3g sine test and those calculated using Equations (3), (8), (11), (13), (15) and (16), together with the measured cooler parameters in Table 1. The data also

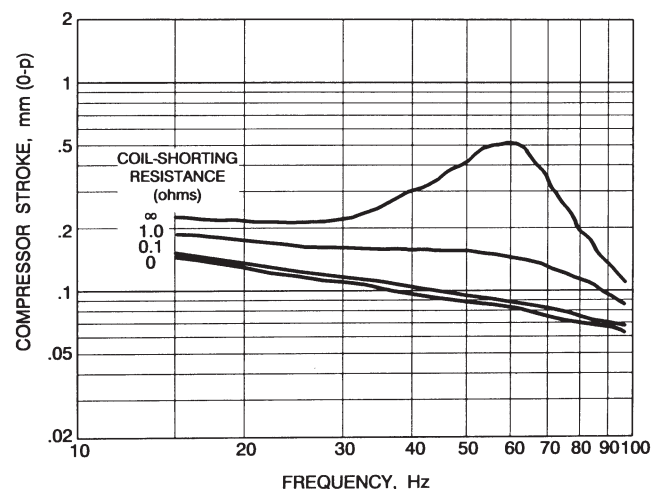


Figure 12 Measured amplitude of compressor piston motion for BAe 55 K cooler during 3g sine sweep with various coil-shortening resistances

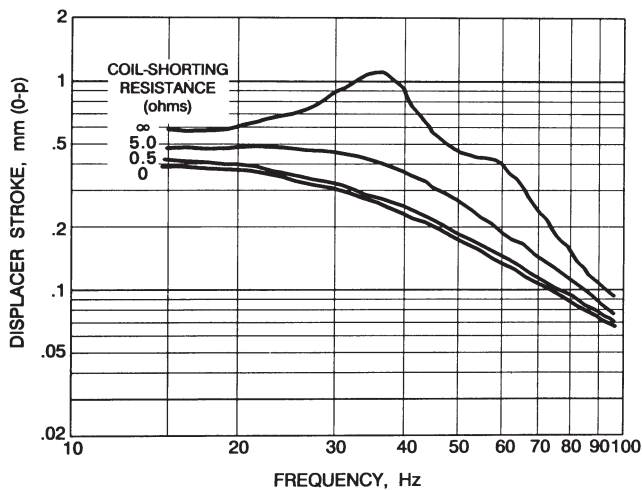


Figure 13 Measured amplitude of displacer motion for BAe 55 K cooler during 3g sine sweep with various coil-shorting resistances

agree quite well with measurements made by BAe on their 80 K cooler.¹³

Drive resonance measurement of stiction

Another challenge facing the designers of mechanical coolers is the unwritten rule that a long-life cryocooler must avoid rubbing surfaces. The flexure bearings and piston clearance seals incorporated into the BAe 55 K Stirling cooler design are examples of the application of this rule. As a trade-off for the exclusion of rubbing surfaces, linear Stirling coolers of this type face the challenge of maintaining tight manufacturing and assembly tolerances and high degrees of cooler dimensional stability over the cooler operating temperature range.

Low frequency stiction testing

One means of verifying the absence of rubbing or contact is the low frequency stiction test. This test technique involves driving the cooler at extremely low frequencies (0.001–1 Hz) and plotting the required

drive current – which is proportional to drive force – versus piston displacement.² At these low frequencies, gas pressure is extremely sensitive to piston clearance, and rubbing is made visible as stiction or discontinuity in the current–displacement plot. This test is useful under a wide variety of post-build environmental conditions and can be applied over the complete operating temperature range of the cooler.

High frequency stiction testing

An alternative method for measuring the presence of stiction is to introduce low level sinusoidal currents at the cooler's natural frequency and gradually increase the level until the threshold current for stiction breakaway is determined. To determine the variation in stiction along the stroke, the measurements are made using various d.c. piston/displacer off-sets. An advantage of this procedure over the low frequency stiction test is that the threshold currents, and thus forces, can be very accurately measured; this is because the stiction-measuring current is a.c., while the positioning current is d.c..

Summary/conclusions

The important common thread linking the achieving of good drive motor efficiency and launch survivability is the dynamic resonant response of the compressor and displacer moving masses. The fundamental equations governing cryocooler mechanical efficiency and launch vibration response have been presented and explored in terms of their implications for cooler design. The resonant frequency, damping and drive motor force parameters associated with the cooler are shown to be key to efficient operation. Means of measuring these parameters are presented and are shown to have broad applicability to additional parameters such as drive stiction and vibration transmitted to the instrument. The resonant parameters of the BAe 55 K cooler have been presented and used to demonstrate the good correlation between the analytical fundamentals and the measured characteristics of a state-of-the-art cryocooler design.

Table 2 Comparison of measured and predicted response to 3g sinusoidal acceleration input as a function of external coil-shorting resistance

External coil-short resistance (Ω)	External resistance plus coil resistance (Ω)	Open-circuit damping, C/C_c	Electrical circuit damping, C_e/C_c	Total damping, $C/C_c + C_e/C_c$	Gain at natural frequency, Q_{Anal}	Measured gain at f_o , Q_{Meas}
Compressor:						
∞	∞	0.20	0	0.20	2.50	2.36
1.0	1.88	0.17	0.55	0.72	0.69	0.64
0.1	0.98	0.17	1.05	1.22	0.41	0.40
0	0.88	0.17	1.17	1.34	0.37	0.36
Displacer:						
∞	∞	0.25	0	0.25	2.00	2.04
5.0	10.6	0.25	0.32	0.57	0.88	0.80
0.5	6.1	0.25	0.55	0.80	0.63	0.52
0	5.6	0.25	0.60	0.85	0.59	0.48

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